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AUTHOR(S) J. P. Lucero
W. D. Zerwekh

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Cineradiography

J. P. Lucero and W. D. Zerwekh
Los Alamos National Laboratory

ABSTRACT

This paper describes a cineradiography system in use at the Los Alamos National Laboratory, as related to the advantages and disadvantages over conventional flash x-ray systems.

Traditionally, x-ray imaging techniques in dynamic testing have relied on creating extremely short pulses of radiation to freeze the motion of the object, and then recording the image on film by means of fluorescent intensifying screens to obtain sufficient image density on the film. This results in images often limited only by the resolution of the film-screen combination, which are usually of reasonable quality.

In a cineradiography system, two basic differences are evident. First, the radiation source emits continuously for the duration of the experiment. Second, the film is replaced by a gated, intensified television camera focused on the fluorescent screeen. The image is frozen by the short gate time of the camera, rather than by the short pulse of radiation.

One advantage of the television system is that the camera can be considerably distant from the screen, and if the screen is sacrificial, mechanical protection requirements are alleviated or eliminated. Another advantage is that several cameras can be focused on the same screen, allowing multiple images to be made with the same geometry. A third advantage is that the spot size of the radiation source is small, thus reducing geometrical limitations on resolution.

The disadvantages of this system relate to the use of the television camera to record the image(s). Neither the resolution nor the contrast of the intensified television camera is as good as film, and this limits the quality of the image that can be produced. However, flash radiographs are often of relatively poor quality because of the limited amount of radiation available from the source and the graininess of the high-speed film required, so this is often not an important difference.

1. INTRODUCTION

For many years, Los Alamos has been using flash x-ray systems (Fig. 1) to produce radiographic images of dynamic events. In these systems, a Marx bank x-ray generator produces a short pulse of radiation, and images are projected on x-ray film. The pulse is typically 30 ns long, which effectively freezes the motion of the experiment. Fast films are used in conjunction with intensifying screens to produce acceptable images for a large number of experiments.

These systems are simple to set up and operate, and the images can be produced at a reasonable price. However, these systems impose several limitations on the images. Usually only one image can be produced because the radiation source, the Marx bank generator, is capable of only one pulse before it must be recharged. If multiple images are required, multiple sources must be used, one for each image. Even with multiple sources, there are spatial limitions on the images. Because each image is produced by a separate source, the field of view changes between images, complicating analysis and allowing less precision than if it were from the same perspective. To prevent washing out the images from stray radiation, elaborate collimation is required so that each film cassette is exposed by only one source.

Another basic limitation is imposed by the protection required for the film cassette. Since many of the dynamic events to be imaged are violent, armor is required in front of the film pack. However, the thickness of armor is constrained to allow x-ray penetration and by the reduction in contrast caused by additional material to be penetrated. This protection problem has prevented acquisition of records for several very violent events where the film could not be sufficiently protected.

To alleviate these limitations, a cineradiography system has been developed in which multiple images can be recorded during an event (Fig. 2). This system uses a source that emits radiation for the entire duration of the experiment. The image formed continuously on a fluorescent screen is similar to the ones used to intensify flash radiographs. Instantaneous images are captured by gated, intensified, solid-state video cameras focused on the screen, one image per camera. This allows multiple, asynchronous images to be recorded, with the minimum duration of each image less than 100 ns. The images are captured remotely on the cameras, so the fluorescent screen need survive only until the last image has been captured. If it is destroyed after that time, no data are lost. Thus, no protection is needed for the screen, as long as it is placed a few centimeters away from the event. Little collimation is required because all images are formed on the same screen. Hence, this system overcomes most of the limitations inherent in flash radiography.

Some disadvantages to this system are related to the use of television as the recording medium. The camera system is more complex than a film pack, requiring more preparation. The dynamic range of the camera sensor is not as wide as x-ray film. The screen-to-camera geometry limits the amount of light available to form the image, so the camera must compensate by having substantial gain, which introduces considerable quantum noise to the image. However, flash radiographs are often relatively poor in quality because the quantity of radiation available from the source is limited and the high speed film required is very grainy, so the definition and contrast are often not as different as might be expected.

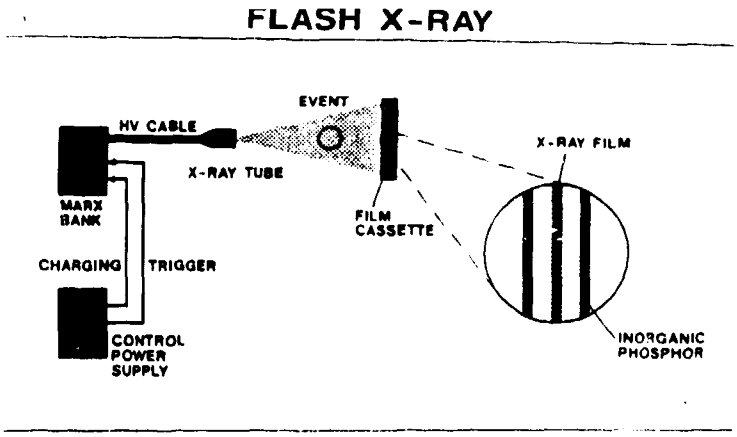

Figure 1.

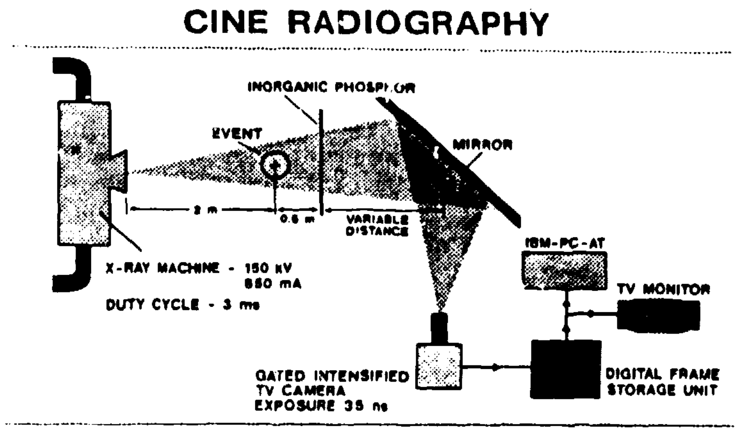

Figure 2.

Also, the radiation source is more complex, and it requires more power than the Marx bank generators used in flash radiography because the duration of the radiation is much longer. Again, this often is not an important consideration, because most of the test sites have adequate power supplies available.

2. EQUIPMENT

The equipment used in the Los Alamos cineradiography system will be described in three sections: first the x-ray source; then the camera system; and finally, the fluorescent screens that convert the x-rays into a visible image.

2.1 X-Ray Source

The source of x-rays used in this system (Fig. 3) was purchased from Technomed, a subsidiary of Precise Optics, Inc. It is a modified, high-output, rotating-anode medical unit, capable of anode to cathode potentials up to 150 kVp, currents up to 850 mA, and pulse widths from 3 ms to several seconds.

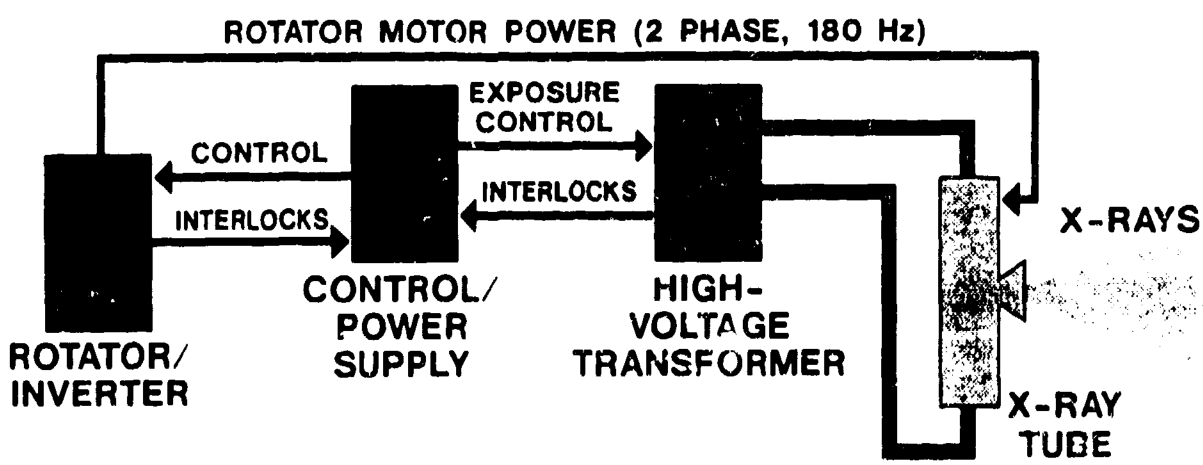

Figure 3.

However, the output is limited in two ways. The first limit is a total power output of 80 kW. The second limit is on anode heating because the anode of the x-ray tube has a heat capacity of 7.07×10^{5} J. The first limit is independent of pulse duration; therefore the maximum current available decreases from 850 mA at 99 kVp to 560 mA at 150 kVp. The second limit is more complex, as it is a function not only of potential and current, but also of pulse duration and repetition frequency. It is met by limiting a single pulse to 1000 mAs, the product of tube current in milliamperes and time in seconds, and by monitoring tube temperature. Even at 150 kVp, a 1000 mAs pulse will produce only a small fraction of the allowable anode heating. The temperature monitor prevents damage by prohibiting additional pulses as the heat limit is approached.

The source consists of several units. The first is the x-ray tube and stand, the next is the high-voltage transformer, then the control console/power supply, and finally, the anode rotator/inverter. The x-ray tube, a standard 150 kV rotating-anode unit, is mounted on a stand which contains a heat exchanger to cool the anode between x-ray pulses. The high-voltage transformer is more complicated than one in a conventional x-ray unit because it must provide output rapidly without overloading the power supply, regardless of the phase of the incoming power. Besides providing controls to set the required voltage, current and pulse duration, the control console/power supply regulates voltage supplied to the high-voltage transformer and provides for interlocks to ensure that power or anode heat limits are not exceeded. The anode rotator/inverter provides a 180 Hz, two-phase supply to the anode rotator motor. The motor spins the anode to approximately 10,800 rpm during the x-ray pulse period, to spread the heat generated over a larger portion of the anode surface. This unit also provides for dynamic braking, to alleviate the possibility of tube breakage when the anode slows through resonance frequencies.

2.2 Camera System

The camera system (Fig. 4), obtained from Xybion Electronic Systems, Inc., also consists of several units; four cameras, a power supply/interconnection unit and a frame grabber for each camera, and a PC-based image analysis system which can obtain an image from any of the frame grabbers.

The cameras are the heart of the imaging system (Fig. 5). Each is a standard charge injection device (CID) video camera to which a gated image intensifier has been fiber optically coupled. The camera uses a CID array configured with 244 pixels vertically by 388 pixels horizontally. In front of this array sensor is the gated intensifier, consisting of a photocathode, a microchannel plate, an output phosphor, and a fiber optic "minifier" coupler. The photocathode is in direct contact with the front of the microchannel plate. The output phosphor is in direct contact with the back, acting as the anode, and is coated on the front of the fiber optic coupler, which is bonded to the CID sensor array. The intensifier input is in 1-in television format, and the output is in 2/3-in format to match the sensor array. The conversion is done with the fiber optic coupler. The fibers are 9 μm in diameter at the input and 6 μm at the output. Therefore, the coupler is referred to as a "minifier." This conversion of formats increases the system resolution and sensitivity.

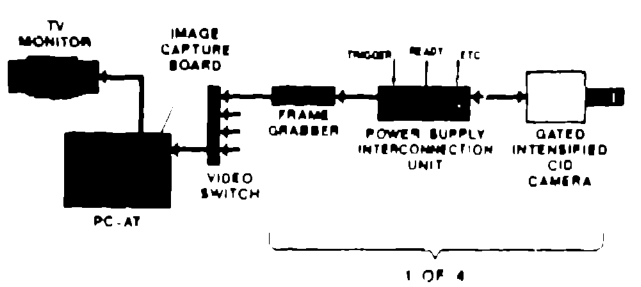

Figure 4

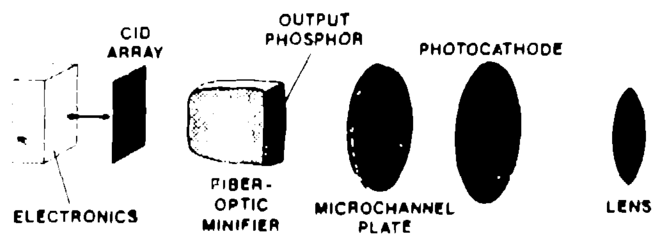

Figure 5

An optical image is focused on the photocathode by a conventional C-mount lens. The photocathode emits electrons in proportion to the incident light intensity, forming an electron image. The electron image is then intensified by the microchannel plate, and reconverted to light by the output phosphor. The luminance gain is typically 18,000 at an input intensity of 2×10^{-6} footcandle. Output brightness is 4 foot lamberts maximum.

The microchannel plate is used as the camera gate (shutter). Intensification occurs only when a voltage is applied across the plate, so that an image is captured on the sensor only while the voltage is present. This voltage is applied once per video field and can be present for as little as 35 ns. Hence, this electronic shutter allows the camera to freeze motion, even for extremely rapid events. This voltage can also be applied continuously, allowing the camera to operate in an ungated mode, which results in maximum sensitivity.

The cameras are capable of operating in three modes: free-run, synchronous (genlock) and refresh. In the free-run mode, all scan and sync signals are internally generated in the camera, independent of the rest of the system. This mode is normally not used with this system. In the genlock mode, all camera scans are synchronized to a master sync source; however, the cameras still run continuously. This mode is typically used to set up the system (to adjust the focus, aperture and gate time of each camera). In the refresh mode, scans are inhibited for 15 fields. In the 16th field a scan is generated to refresh (erase accumulated noise on) the CID sensor. During the 15 field period, a trigger signal received by the camera control will generate a gate to the intensifier and cause a scan to be generated at the next field time. This image is then stored in a frame grabber. The refresh periods on all cameras are synchronized so that all cameras are ready during the same intervals.

The power supply/interconnection unit provides a regulated power source for the camera electronics. It also provides optically isolated buffers and drivers for the camera control signals (genlock, refresh, inhibit, gate trigger, etc.) and it routes the camera video and capture signals to the frame grabber.

The frame grabber is a six-bit analog-to-digital converter, which digitizes the video from the camera and stores the image in memory. After the image is stored, it is output continuously (after reconversion) as a video signal that can be displayed on a monitor or transferred to the image analysis system.

The image analysis system consists of an image capture board in a slot in the PC, and software that allows the PC to perform a number of metric and enhancement tasks on the stored images. The board can receive images from all four camera frame grabbers, and its memory can store up to 13 images. An additional 60 to 130 images (depending on the resolution selected) can be stored on a hard disk. When an operator identifies cogent points on the image or series of images, the software can give distance, velocity, acceleration, and vector information about the test object. By means of a series of enhancement algorithms, the software also enables a user to bring out details that are difficult to identify in the original image.

2.3 Fluorescent Screens

The operating concept of the cineradiography system places different requirements on the fluorescent screens than the screens used in flash radiography. In flash systems, the motion is frozen by the short duration of the radiation, so the decay constant of the screen is unimportant. In the cineradiography system the decay constant can be the limiting constraint on temporal resolution. Hence, screens used in this application require the shortest possible decay. The color of the fluorescence is also important. The photocathode in the camera is significantly more sensitive to green light than it is to blue. Again, this differs from film as the imaging medium because film sensitivity tends to increase with decreasing wavelength of the incident light. Several screens have been tried; the results are shown below in Table 1.

Table 1. Screens used with system

Screen	Mfgr	Composition	Sensitivity
Quanta III	DuPont	LaOBr	Poor
Rarex G100	MCI	$Gd_2O_2S{:}Tb$	Poor
Optex PFG	MCI	ZnCdS:Ag	Best
NDT-9	DuPont	$CaWO_4$	Poor
Trimax 12	3M Co.	$Gd_2O_2S{:}Tb$	Poor
Trimax 8	3M Co.	$Gd_2O_2S{:}Tb$	Poor
Hi Plus	DuPont	$CaWO_4$	Poor
Rarex FSL-1	MCI	$Gd_2O_2S{:}Pr$	Good
Sodium Iodide	Harshaw	NaI	Poor

The most sensitive screen tried so far has been an MCI Optex PFG, which has the same composition as a P-20 phosphor. This screen also has an extremely short decay constant, so it is our screen of choice at this point in time.

3. APPLICATIONS

Results have been obtained in various applications of the system. Several of these are hybrid applications, where the radiation source used was a Marx generator. In these, the camera system was used because a film cassette would not have survived the event, but the camera stand-off distance allowed an image to be captured.

Example 1. Camera System Acceptance Test (Figs. 6 and 7)
X-ray generator: 180 kV Marx bank
Screen: FSL-1
Source to screen distance: 50 cm
Screen to camera distance: 2 m
Object to screen distance: Contact
Radiation pulse length: 30 ns
Camera gate: 35 ns
Lens settings: f1.8, 60mm (16-160mm f1.8 lens)
Test objects: Definition gauges, lead letters

Figure 6.

Figure 7.

Example 2. High Explosive Driven Plate (Figs. 8 and 9)

X-ray generator: 450 kV Marx bank
Screen: FSL-1
Source to screen distance: 3 m
Screen to camera distance: 3 m
Object to screen distance: 20 cm
Radiation pulse length: 30 ns
Camera gate: 6 μs
Lens settings: f2, 75mm (16-160mm f1.8 lens)
Test objects: 8 lbs HE (PBX 9501) driving 0.125" Al plate

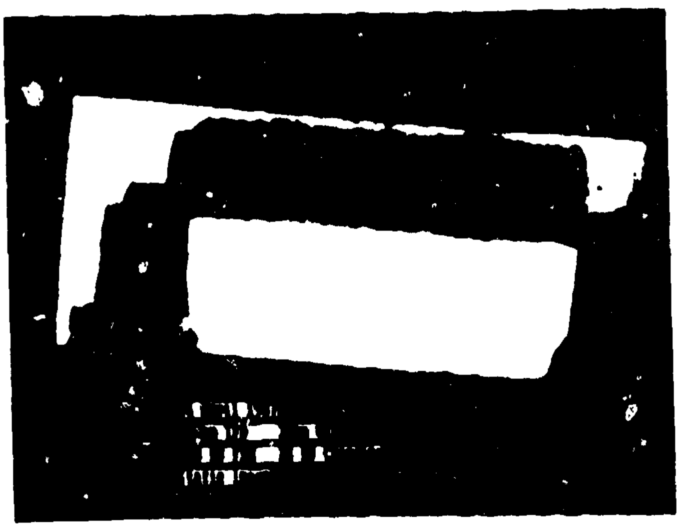

Figure 8.

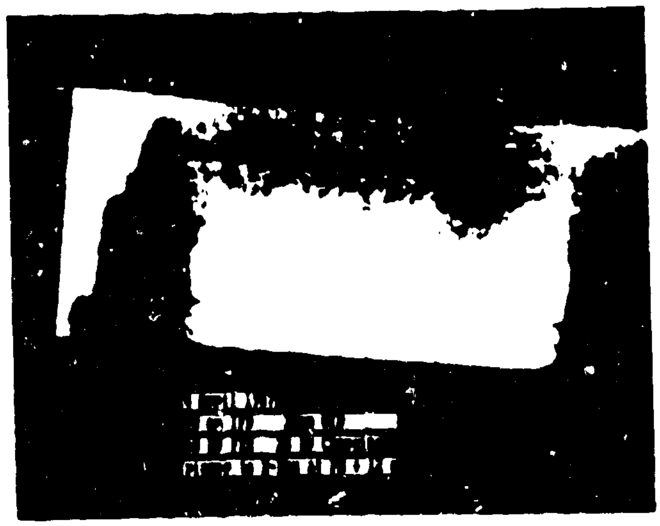

Figure 9.

Example 3. System Proof of Principle

X-ray generator: 150 KV, 560 mA as described above
Screen: PFG
Source to screen distance: 50 cm
Screen to camera distance: 1.2 m
Object to screen distance: Contact
Radiation pulse length: 3 ms
Camera gate: 100 ns
Lens settings: f0.95, 50mm
Test objects: Lucite step wedge, lead numbers